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THE PRODUCTION OF POWDER-METALLURGY TUNGSTEN SHEET AND PLATE

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SUMMARY

A brief review and analyses is presented of the tungsten sheet rolling program performed by the Fansteel Metallurgical Corporation for the Department of the Navy, Bureau of Naval Weapons, on Contract No. NOw-60-0621-c. Emphasis is placed on detailing the procedures which were evolved for the production of 113 plates and sheets of various gages. These materials are now being evaluated for physical and mechanical properties as well as for formability characteristics on three other current Navy programs.

INTRODUCTION

This memorandum was prepared by the Defense Metals Information Center in support of the Refractory Metals Sheet Rolling Program. This program was established by the Department of the Navy, Bureau of Naval Weapons, to accelerate the development of production techniques for high-quality sheet products from the refractory metals. Since its establishment, the program has been expanded into an integrated Department of Defense program which now involves approximately twelve contracts. These are under the surveillance of the Materials Advisory Board Refractory Metals Sheet Rolling Panel. The individual contracts are supported and managed by either the Department of Navy, Bureau of Naval Weapons, or the U.S. Air Force, Aeronautical Systems Division, Manufacturing Technology Laboratory.

The purpose of this memorandum is to present a brief review, analyses, and summary of the tungsten sheet rolling program completed by the Fansteel Metallurgical Corporation for the Bureau of Naval Weapons on Contract No. NOw-60-0621-c. The memorandum features a compact summary of the procedures which were ultimately evolved for the production of tungsten plate and sheet of various gages and includes those physical- and mechanical-property data which were determined on this "pedigreed" production material.

It should be noted that no extensive property determinations on the production material were intended as a part of the Fansteel program. Rather, a thorough evaluation of much of this material is being pursued on three other Navy contracts. These are identified as follows:

Contract No.	Contractor	Contract Objectives
N600(19)-59530	Southern Research Institute	To determine the mechanical and physical properties of TZM molybdenum alloy sheet and tungsten sheet.
NOw-63-0542-c	Super-Temp Corporation	To perform a comparative evaluation of the formability of tungsten plate and sheet by spinning techniques.
NOw-63-0786-d	Solar Aircraft	To determine and demonstrate the fabrication characteristics of tungsten sheet.

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The Defense Metals Information Center presents this information in the belief that it will be of value to all who are interested in correlating the fabrication history of refractory sheet metal to the end properties which are obtained on this material.

DESCRIPTION OF PROGRAM

Objective

To develop the material and processes for producing high-quality tungsten or tungsten alloy sheet, using powder metallurgy techniques.

Approach

1. Conduct literature and state-of-art survey.
2. Select candidate powders and evaluate for:
   a. Powder characteristics
   b. Consolidation properties
   c. Workability
3. Sheet process evaluation
   a. Evaluation of:
      (1) Rolling temperature
      (2) Rolling reduction
      (3) Degree of cross rolling
      (4) Process heat treatments.
   b. Preparation of a minimum of ten full-scale pilot sheets, each nominally 0.060 x 18 x 48 inches.
4. Production phase
   a. Initial plans*; rolling of 3500 pounds of sheet, each nominally 0.060 x 18 x 48 inches.
   b. Modified plans; rolling of:
      (1) 0.250-inch-thick plate, 75% cold work
      (2) 0.100-inch-thick sheet, 90% cold work
      (3) 0.060-inch-thick sheet, 94% cold work
      (4) 0.020-inch-thick sheet, 98% cold work
      (5) 0.020-inch-thick sheet, 89% cold work
      (6) 0.010-inch-thick sheet, 99% cold work
      (7) 0.010-inch-thick sheet, 89% cold work

MAJOR ACCOMPLISHMENTS OF PROGRAM

Powder Evaluation

1. Provided cross evaluation between consolidation and workability of the 18 different types and blends of doped and undoped powders listed in Table 1.
   a. Undoped powder, Lots 101 and 102 x 20, possessed the best all around combination of consolidation and workability relative to the facilities used. Consequently, Lot 102 x 20 and one similar (Lot A5467) were used for the full-scale pilot and production phases, respectively. Figure 1 shows the particle size distribution and analysis of the Lot 102 x 20 material.
   b. The alkali-silicate-aluminum doped powder, Lot J-5, was the only alkali-silicate candidate which showed any promise for meeting sintered density requirements.

* These plans abandoned by contract modification after completion of Step 3b, above.

c. The alkali-1 per cent thoria lot, No. T-34, possessed reasonable consolidation and working properties, and displayed excellent short-time elevated temperature strength.

d. The sintering of massive alkali-doped bars did not appear to be practical with the furnace design used.

2. Established techniques for pressing and sintering large-size sheet bars of the selected undoped powder.

a. Production-size bars, measuring nominally 1 x 6 x 13 inches and weighing 55 pounds each, were isostatically compacted under a pressure of 35,000 psi.

b. These bars were induction-sintered in a hydrogen atmosphere to give a density variation of no more than 2 per cent with the minimum density level at approximately 93 per cent of theoretical density. The following sintering schedule was used:

Time to Temperature, hours	Temperature, C	Time to Temperature, hours
4	1700	1
4	2300	9

Sheet Process Evaluations

The pre-pilot sheet process evaluations established the desirability of:

1. Using rolling temperatures in the interval of 1450 to 1150 C. This resulted in material with the most uniform structure and best material surface.

2. Avoiding in-process recrystallization treatments.

a. All material recrystallized at the completion of intermediate rolling subsequently split during later rolling.

b. Highest yields and lowest bend transition temperature were favored for sheet which received no in-process recrystallization treatments. (For example, see Table 2.)

3. Finishing sheet with a high degree of total deformation. Transition temperatures decreased with increasing total deformation after annealing. The lowest transition temperature occurred with no in-process annealing. (See Table 2.)

4. Maintaining balanced reductions in the longitudinal and transverse directions to minimize bend anisotropy. Lowest transition temperatures occurred with a 1:1 ratio between cross rolling directions whereas the highest occurred for straight rolled material.

Production Plate and Sheet Material Produced

The culmination of this program was the development of rolling practices for producing the following quantity of production plate and sheet material:

1. 21 plates, nominally 0.250 x 14 x 18 inches
2. 29 sheets, nominally 0.100 x 18 x 30 inches
3. 31 sheets, nominally 0.060 x 18 x 48 inches
4. 13 sheets, nominally 0.020 x 18 x 30 inches
5. 19 sheets, nominally 0.010 x 18 x 24 inches.

Tables 3-6 list the dimensions and flatness data determined for each of the individual plates and sheets produced. These tables also list references to succeeding tables which detail the specific rolling schedules used (Tables 7-11, inclusive) and which contain property data determined on this program for these materials (Tables 12-20, inclusive).

Tables 3-6 also indicate the disposition of the production plate and sheet generated on this program. As shown in Tables 3-5, a limited amount of the 0.25-, 0.10-, and 0.060-inch-thick material had not been committed to test programs as of the date of this report. This material is being reserved by the Bureau of Naval Weapons (RRMA-2) for those Government contractors pursuing programs which will yield needed data on the fabricability, or related properties, of the RMSP sheet.

LIMITATIONS OF PROGRAM

Equipment Limitations

1. Sintering Furnace

a. Due to design limitations, it was not practical to sinter massive alkali-doped bars despite the promise shown by some of these materials in the preliminary studies. The difficulty with sintering massive bars was due to evolution of the volatile alkali dopants which tended to plug the hydrogen exhaust ports and also to flux the refractory furnace lining. As a consequence, the choice of powder type for the production phase was restricted to undoped tungsten powder.

b. Temperature limitations of the sintering equipment (maximum permissible temperature of 2300 C) forced a compromise in sintered density and structure in the massive bars. Thus, one important conclusion was that consideration should be given to the goal of attaining temperatures on the order of 2600 to 2700 C and shortened sintering times to achieve improved sintered rolling billets.

2. Rolling Mill

The production rolling mill used was designed only for minimum single rolling of thicknesses no lighter than 0.060-inch thick. This necessitated the use of pack rolling techniques for the production of the 0.020- and 0.010-inch-thick sheet which, accordingly, was adjudged as not qualifying as "extremely reliable material".

Program Modification

On completion of preparing the full-scale pilot sheet, the program was modified to produce plate of 0.25-inch thickness and sheet of 0.020- and 0.010-inch thickness in addition to 0.060-inch-thick material. Due to limitations in time and funding, it was not possible to optimize the fabrication procedures for material other than the 0.060-inch-thick sheet.

Reporting Details

Due to changes in personnel over the period of performance on this program, some details in processing some of the 0.010- and 0.020-inch-thick sheet were not recorded and/or reported. Hence, the total history of some of these materials is uncertain.

TABLE 1. CHARACTERISTICS OF POWDER LOTS AND BLENDS EVALUATED

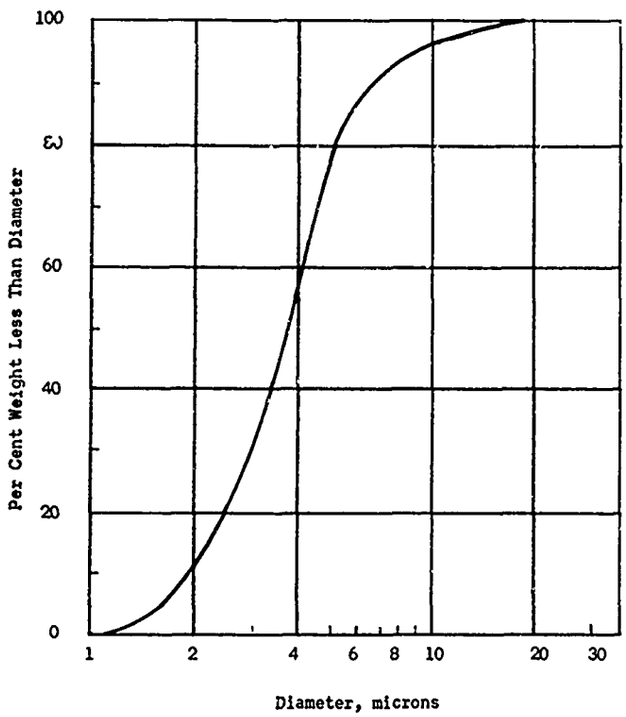
Code No.	Lot or Blend No.	Type	Average Particle Size, microns	Scott Density, g/in.^{3}
1	5WL-137-C5	Undoped	1.18	34.5
2	APT-3-A	Undoped	7.10	70.4
3	J-1	Alkali-silicate doped	6.00	47.8
4	J-2	Alkali-silicate-carbon doped	5.80	52.5
5	J-3	Alkali-silicate doped	5.60	54.2
6	J-4	Alkali-silicate doped	4.80	51.0
7	J-5	Alkali-silicate-aluminum doped	4.30	52.2
8	10WL-140-4A	Undoped	4.30	49.8
9	WT-831	Undoped	6.10	90.8
10	101	Undoped	3.90	59.5
11	SDS	Undoped	3.60	56.4
12	T-34	Alkali-thoria doped	4.80	60.4
13	67% APT-3A 33% ND4104	Undoped blend	2.60	61.2
14	67% J-4 33% ND4104	Undoped and doped blend	2.00	43.8
15	38% 10WL-140-4A 25% 5WL-137-C5 23% APT-3A 11% ND4104	Undoped blend	2.50	54.6
18	APT-3B	Undoped	5.00	79.3
19	APT-4-12-1	Undoped	1.15	45.2
20	102 x 20	Undoped	3.65	67.7

TABLE 2. SELECTED DATA SHOWING EFFECTS OF ROLLING VARIABLES ON BEND DUCTILITY OF EXPERIMENTAL TUNGSTEN SHEET

Note: All sheet rolled to 0.060-inch thickness from 1 x 4 x 4-inch bars and tested after a 10-minute stress-relief anneal at 1100 C.

Code No.	Processing Annealing Thickness, inch	Cross Rolling Thickness, inch	Bend Transition Temperature, F	
			Transverse(a)	Parallel(a)
1-2	0.4, 0.17	Not done	750	-
1-13	0.4, 0.17	Not done	750	-
1-1	0.4	Not done	600	-
1-2	0.4	Not done	600	-
2-2	0.4	0.62	425	300
1-5	0.4	0.27	375	220
2-1	Not done	0.27	320	180

(a) Test direction relative to final rolling direction.



Impurity Element	Content, wt pct	Impurity Element	Content, wt pct
O	0.026	Fe	0.001-
N	0.0005	Mg	0.001-
C	0.001	Mn	0.001-
Ag	0.001	Mo	0.010
Al	0.001-	Ni	0.001-
Ca	0.001-	Si	0.005-
Cu	0.001		

FIGURE 1. PARTICLE SIZE DISTRIBUTION AND CHEMICAL ANALYSIS OF LOT 102 x 20 POWDER SELECTED FOR FULL-SCALE PILOT PHASE

TABLE 3. LOG OF 0.25-INCH-THICK PRODUCTION PLATE

Plate No.	Dimensions, inches: Thickness: Maximum	Thickness: Average	Thickness: Minimum	Length	Width	Flatness, per cent	Table References for: Fabrication History	Property Evaluations on Finished Sheet: Chemistry	Tensile Property	Hardness	Sheet Disposition(a)
79	0.260	0.258	0.255	20	13	--	7	--	--	--	--
98	0.263	0.260	0.257	17	14	--	7	--	--	--	--
99	0.262	0.254	0.247	19	14	--	7	--	--	20	--
100	0.263	0.260	0.257	19	13	--	7	--	--	--	ST
102	0.263	0.261	0.259	21	13	--	7	--	--	--	--
103	0.260	0.258	0.254	18	14	--	7	--	--	20	--
104	0.263	0.262	0.260	20	14	--	7	--	--	--	ST
105	0.261	0.259	0.255	20	13	--	7	--	--	--	--
106	0.262	0.258	0.253	20	14	--	7	--	--	--	--
107	0.263	0.257	0.247	17	13	--	7	--	--	--	--
108	0.262	0.258	0.255	21	13	--	7	--	--	--	ST
109	0.259	0.255	0.250	16	13	--	7	--	--	--	--
110	0.259	0.256	0.250	10	14	--	7	12	13	20	--
111	0.262	0.259	0.257	17	14	--	7	--	--	--	ST
113	0.260	0.257	0.253	20	14	--	7	--	--	--	ST
114	0.262	0.262	0.261	20	13	--	7	--	--	--	--
115	0.261	0.258	0.253	20	13	--	7	--	--	--	ST
117	0.262	0.259	0.257	17	13	--	7	--	--	--	--
119	0.263	0.257	0.254	21	13	--	7	--	--	--	ST
120	0.258	0.257	0.255	20	14	--	7	--	--	--	ST
124	0.263	0.258	0.249	19	13	--	7	--	--	--	ST

(a) ST designates material sent to Super-Temp Corporation for evaluation under Contract NOw-63-0542-c. Approximately 11 of the 12 remaining plates were uncommitted to test programs as of May 15, 1964.

TABLE 4. LOG OF 0.100-INCH-THICK PRODUCTION SHEET

Plate No.	Dimensions, inches: Thickness: Maximum	Thickness: Average	Thickness: Minimum	Length	Width	Flatness, per cent	Table References for: Fabrication History	Property Evaluations on Finished Sheet: Chemistry	Tensile Property	Hardness	Sheet Disposition(a)
3	0.102	0.101	0.098	30	19	4.6	8	--	--	--	SA
4	0.105	0.104	0.101	31	19	1.0	8	--	--	--	--
48	0.103	0.102	0.100	30	19	2.6	8	--	--	--	SA
49	0.102	0.100	0.096	30	19	2.1	8	--	--	--	SA
51	0.105	0.104	0.102	31	19	1.5	8	--	--	--	SA
55	0.102	0.101	0.096	29	19	1.3	8	--	--	--	SA
56	0.105	0.102	0.099	32	19	1.0	8	--	--	--	SA
57	0.105	0.103	0.096	30	19	4.9	8	--	--	--	--
58	0.103	0.102	0.098	32	19	1.0	8	--	--	--	SA
59	0.105	0.104	0.103	31	19	1.0	8	--	--	--	--
60	0.104	0.102	0.100	29	19	1.4	8	--	--	--	--
61	0.105	0.105	0.104	31	19	2.3	8	--	--	--	SA
64	0.103	0.100	0.098	29	19	1.8	8	--	--	--	SA
65	0.104	0.102	0.100	31	19	2.3	8	--	--	--	SA
66	--	--	--	--	--	-	8	12	14,18	20	--
68	--	--	--	--	--	-	8	12	14,18	20	--
71	--	--	--	--	--	-	8	12	14,18	20	--
76	0.105	0.103	0.100	30	19	1.0	8	--	--	--	SA
101	0.103	0.102	0.100	32	19	2.3	8	--	--	--	--
112	0.105	0.102	0.099	31	19	4.0	8	--	--	--	SRI
116	0.104	0.103	0.100	28	19	3.4	8	--	--	--	--
118	0.103	0.101	0.098	31	19	4.2	8	--	--	--	--
121	0.103	0.102	0.099	33	19	1.8	8	--	--	--	--
122	0.103	0.102	0.100	14	19	1.1	8	12	14,18	20	--
123	--	--	--	--	--	-	8	12	14,18	20	--
125	0.103	0.099	0.097	34	19	2.3	8	--	--	--	--
126	0.104	0.103	0.101	33	19	2.1	8	--	--	--	--
127	0.104	0.103	0.101	32	19	1.7	8	--	--	--	--
128	0.103	0.102	0.101	13	19	2.5	8	12	14,18	20	--

(a) SA and SRI designate material sent to the Solar Aircraft Company and to the Southern Research Institute for evaluation under Contracts NOw-63-0786-d and N600(19)-59530, respectively. Approximately 12 of the 17 remaining sheets were uncommitted to test programs as of May 15, 1964.

TABLE 5. LOG OF 0.060-INCH-THICK PRODUCTION SHEET

Plate No.	Dimensions, inches: Thickness: Maximum	Thickness: Average	Thickness: Minimum	Length	Width	Flatness, per cent	Table References for: Fabrication History	Property Evaluations on Finished Sheet: Chemistry	Tensile Property	Bend Property	Hardness	Sheet Disposition[a]
1A	0.063	0.061	0.057	49	21	4.9	9	--	--	--	--	SA
2A	0.063	0.061	0.058	50	21	4.1	9	--	--	--	--	SA
3A	0.062	0.061	0.059	49	21	6.2	9	--	--	--	--	SA
4A	0.065	0.061	0.057	48	21	5.4	9	--	--	--	--	SA
5A	0.062	0.059	0.058	30	21	4.2	9	--	--	--	--	SA
6A	0.058	0.057	0.055	25	19	1.6	9	--	--	--	--	SA
7A	0.062	0.061	0.059	31	21	2.9	9	--	--	--	--	SA
8A	--	--	--	--	--	-	9	--	--	--	--	--
9A	--	--	--	--	--	-	9	--	--	--	--	--
10A	0.063	0.061	0.059	51	21	3.1	9	--	--	--	--	SA
11A	0.061	0.059	0.057	51	19	3.4	9	--	--	--	--	SA
12A	0.063	0.062	0.060	49	21	5.5	9	--	--	--	--	--
1	0.063	0.061	0.058	30	19	4.3	9	12	15,17,18	19	20	--
2	0.061	0.059	0.057	45	21	7.9	9	--	--	--	--	ST
3	0.062	0.059	0.058	46	21	2.5	9	--	--	--	--	--
4	0.062	0.060	0.058	45	20	7.7	9	--	--	--	--	--
5	0.062	0.060	0.058	47	21	4.8	9	12	15,17,18	19	20	ST
6	0.060	0.059	0.058	45	21	3.1	9	12	15,17,18	19	20	SRI
7	0.063	0.058	0.057	48	21	3.1	9	12	15,17,18	19	20	--
8	0.063	0.060	0.057	48	21	5.1	9	--	--	--	--	ST
9	0.062	0.059	0.057	47	21	3.7	9	--	--	--	--	ST
10	0.063	0.060	0.056	29	21	2.5	9	12	15,17,18	19	20	--
11	0.061	0.058	0.057	45	19	4.5	9	--	--	--	--	ST
12	0.061	0.059	0.058	48	21	3.4	9	--	--	--	--	--
13	0.061	0.059	0.057	48	19	2.8	9	--	--	--	--	ST
14	0.061	0.059	0.058	49	19	3.8	9	--	--	--	--	ST
15	0.062	0.059	0.057	48	21	2.3	9	--	--	--	--	SRI
16	0.063	0.060	0.058	48	21	4.9	9	--	--	--	--	--
17	0.063	0.061	0.059	51	21	-	9	--	--	--	--	SRI
18	0.063	0.059	0.057	43	21	3.4	9	--	--	--	--	--
19	0.061	0.059	0.060	29	21	2.0	9	12	15,17,18	19	20	--

(a) SA, ST, and SRI designate material sent to the Solar Aircraft Company, the Super-Temp Corporation, and to the Southern Research Institute for evaluation under Contracts NOw-63-0786-d, NOw-63-0542-c, and N600(19)-59530, respectively. Approximately 5 of the remaining 12 sheets were uncommitted to test programs as of May 15, 1964.

TABLE 6. LOG OF 0.010-INCH AND 0.020-INCH THICK PRODUCTION SHEET

Plate No.	Dimensions, inches: Thickness: Maximum	Thickness: Average	Thickness: Minimum	Length	Width	Flatness, per cent	Table References for: Fabrication History	Property Evaluations on Finished Sheet: Chemistry	Tensile Property	Hardness	Sheet Disposition[a]
						0.020-Inch-Thick Sheet					
1RX	0.021	0.020	0.019	27	14	2.6	10	--	--	--	--
2RX	0.022	0.020	0.019	27	14	2.5	10	--	--	--	--
1-2	0.021	0.020	0.019	25	18	4.6	10	--	--	--	SA
2-1	0.021	0.020	0.019	30	18	4.2	10	--	--	--	SA
2-2	0.021	0.020	0.019	30	18	2.8	10	--	--	--	SA
3-1	0.021	0.019	0.019	33	18	3.1	10	--	16	--	--
3-2	0.021	0.020	0.019	33	18	4.7	10	--	--	--	--
4-1	0.021	0.020	0.019	33	18	4.9	10	--	--	--	SA
4-2	0.019	0.019	0.019	33	18	2.8	10	--	--	--	SA
5-1	0.020	0.019	0.019	34	19	2.8	10	12	16	20	--
5-2	0.021	0.020	0.019	33	18	3.9	10	--	--	--	--
6-1	0.022	0.020	0.019	32	18	4.0	10	--	--	--	SA
6-2	0.021	0.020	0.019	30	16	3.9	10	--	--	--	SA
						0.010-Inch-Thick Sheet					
1	0.011	0.010	0.010	26	18	4.7	11	12	16	20	SA
2	0.011	0.010	0.009	26	18	2.7	11	--	--	--	--
3	0.010	0.010	0.009	25	17	5.0	11	--	--	--	--
4	0.010	0.010	0.009	26	18	5.2	11	--	--	--	--
5	0.010	0.010	0.009	36	16	8.8	11	--	--	--	SA
6	0.010	0.010	0.009	25	18	4.7	11	--	--	--	--
7	0.011	0.010	0.009	26	18	4.9	11	--	--	--	SA
8	0.011	0.010	0.010	26	18	8.0	11	--	--	--	SA
9	0.010	0.010	0.009	25	18	4.7	11	--	--	--	SA
10	0.011	0.010	0.009	26	16	4.1	11	--	--	--	SA
11	--	--	--	--	--	-	11	--	--	--	--
12	0.009	0.009	0.008	26	17	3.7	11	--	--	--	SA
13	0.011	0.010	0.010	26	17	4.1	11	--	--	--	SA
14	0.011	0.010	0.009	26	17	4.4	11	--	--	--	SA
15	0.010	0.010	0.009	26	17	3.9	11	--	16	20	SA
16	0.009	0.009	0.008	20	17	4.1	11	--	--	--	SA
17	0.010	0.009	0.009	27	17	6.2	11	--	--	--	SA
18	0.011	0.010	0.009	26	17	4.7	11	--	--	--	SA

(a) SA designates material sent to the Solar Aircraft Company for evaluation under Contract NOw-63-0786-c. All of the remaining 0.010- and 0.020-inch-thick sheets have been committed to other test programs.

TABLE 7. ROLLING SCHEDULE FOR 0.250-INCH-THICK PLATE

Pass No.	Mill Setting, inch	Temp, C	Comments
	A. Breakdown and Intermediate Rolling (All Material)		
1	0.900	1450-1500	Long rolled
2	0.700	1450-1500	Cross rolled after Pass 1
3	0.500	1450-1500	
4	0.325	1450-1500	
5	0.325	1350-1400	Flat pass
6	0.300	1350-1400	Cross rolled, stress relieved 10 minutes at 1200 C, caustic cleaned and acid etched, inspected, and conditioned

Plate No.	Pass No.	Mill Setting, inch	Temp, C	Comments
	B. Finish Rolling			
98	1	0.240	1240	Rolling of all plate was in same direction as last pass in intermediate rolling
	2	0.300	1240	
99	1	0.238	1250	
	2	0.300	1250	
	3	0.300	1250	
104	1	0.230	1290	
	2	0.310	1260	
107	1	0.230	1290	
	2	0.310	1290	
	3	0.298	1260	
113	1	0.220	1300	
	2	0.300	1260	
	3	0.285	1260	
117	1	0.230	1250	
	2	0.297	1240	
	3	0.297	1240	
	4	0.297	1240	
79, 100, 102, 103, 105, 106, 108, 109, 110, 111, 114, 115, 119, 120, 124	1	0.220	1300	
	2	0.285	1250	All plates finished with stress relief of 10 minutes at 1050 C, caustic cleaned, and acid etched
			1260	

TABLE 8. ROLLING SCHEDULE FOR 0.100-INCH-THICK SHEET

Sheet No.	Pass No.	Mill Setting, inch	Temp, C	Comments
	A. Breakdown and Intermediate Rolling			
101, 112, 116, 118, 121, 122, 123, 125, 126, 127, 128	1	0.900	1475	Long rolled
	2	0.700	1475	Cross rolled after Pass 2
	3	0.500	1475	
	4	0.300	1475	
	5	0.215	1375	
	6	0.215	1375	Cross rolled after Pass 6
	7	0.150	1375	
	8	0.140	1375	Stress relieved 10 minutes at 1175 C, caustic cleaned and acid etched, inspected and conditioned
3, 4, 48, 49, 51, 55, 56, 57, 58, 59, 60, 61, 64, 65, 66, 68, 71, 76	1	0.900	1450	Long rolled
	2	0.750	1400	Cross rolled after Pass 2
	3	0.600	1400	
	4	0.490	1400	
	5	0.400	1400	
	6	0.330	1400	Cross rolled after Pass 6
	7	0.270	1350	
	8	0.235	1350	Stress relieved 5 minutes at 1150 C, caustic cleaned and acid etched, inspected and conditioned

Sheet No.	Pass No.	Mill Setting, inch	Sheet Thickness, inch	Temp, C	Comments
	B. Finish Rolling				
3	1	0.100	0.175	1300	Rolling of all sheet was in same direction as last pass in intermediate rolling
	2	0.075	0.145	1270	
	3	0.050	0.123	1120	
4, 49, 64	1	0.100	0.180	1330	
	2	0.075	0.155	1300	
	3	0.050	0.125	1280	
48, 56, 57, 58	1	0.100	0.187	1330	
	2	0.075	0.157	1270	
	3	0.050	0.135	1250	
	4	0.050	0.120	1215	
51, 76	1	0.100	0.187	1310	
	2	0.075	0.157	1280	
	3	0.050	0.135	1250	
	4	0.050	0.120	1200	
55	1	0.100	0.187	1340	
	2	0.075	0.155	1280	
	3	0.040	0.138	1150	
	4	0.040	0.120	1150	
59, 60	1	0.100	0.180	1315	
	2	0.075	0.150	1300	
	3	0.050	0.125	1260	
61, 65	1	0.100	0.185	1330	
	2	0.075	0.155	1310	
	3	0.050	0.136	1150	
	4	0.050	0.127	1130	
66	1	0.100	0.175	1300	
	2	0.075	0.145	1290	
	3	0.050	0.125	1210	
68(a)	1	0.100	—	1335	
	2	0.075	0.140	1070	
	3	0.050	0.120	1070	
71(a)	1	0.100	0.179	1300	
	2	0.075	0.150	1070	
	3	0.050	0.121	1040	All sheet finished with stress relief of 10 minutes at 1150 C, caustic cleaned and acid etched.

(a) Sheets 68 and 71 cracked during rolling and were finished in two sections each.

TABLE 9. ROLLING SCHEDULE FOR 0.060-INCH-THICK SHEET

Pass No.	Nominal Thickness, inch	Temp, C	Comments
	A. Breakdown and Intermediate Rolling (All Material)		
1	0.800	1450	Long rolled
2	0.625	1400	Cross rolled after Pass 2
3	0.500	1400	
4	0.400	1400	Stress relieved 5 minutes at 1300 C/1350C
5	0.325	1350	
6	0.270	1300	Cross rolled after Pass 6
7	0.215	1300	
8	0.175	1300	Stress relieved 5 minutes at 1250 C/1300 C, caustic cleaned and acid etched, inspected and conditioned

Sheet No.	Pass No.	Nominal Thickness, inch	Temp, C	Comments
	B. Finish Rolling			
1A-12A, incl., plus 19(a)	1	0.138	1250	Rolling of all sheet was in same direction as last pass in intermediate rolling
	2	0.111	1200	
	3	0.089	1200	
	4	0.071	1150	
	5	0.064	1150	
1-18, incl.	1	0.138	1250	
	2	0.111	1200	
	3	0.090	1200	
	4	0.075	1050	

Sheets 1-18 were then paired into 2-sheet packs and pack-rolled at 1050 C as follows:

Pack No.	Sheet Nos.	No. of Passes	Sheet Thickness, inch	Comments
1	1, 2	2	0.069, 0.067	Rolling was continued in same direction as in last previous pass
2	3, 4	3	0.068, 0.065	
3	5, 6	3	0.066, 0.066	
4	7, 8	2(b)	0.065, 0.067	
5	9, 10	1(b)	0.065, 0.065	
6	11, 12	2	0.068, 0.069	
7	13, 14	1(b)	0.065, 0.068	
8	15, 16	3	0.062, 0.063	
9	17, 18	3(b)	0.065, 0.063	

All finished sheets were stress relieved 5 minutes at 1150 C, caustic cleaned, and acid etched.

(a) Sheet 19 was single rolled from 0.090-inch to 0.064-inch in eight passes, reheating to 1050 C before each pass.

(b) Individual sheets also given 1 to 5 flat passes after pack rolling.

TABLE 10. ROLLING OF 0.020-INCH-THICK SHEET

Pass No.	Mill Setting, inch	Temp, C	Comments
			A. Breakdown Rolling (All Material)
1	0.900	1475	Long rolled
2	0.700	1475	Cross rolled after Pass 2
3	0.500	1475	
4	0.300	1475	
5	0.215	1375	
6	0.215	1375	Cross rolled after Pass 6
7	0.150	1375	
8	0.140	1375	Stress relieved 5 minutes at 1150 C, caustic cleaned and acid etched, inspected, and conditioned. Plate size nominally 0.23 inch x 10 inch x 16 inch

B. Intermediate Rolling (All Material)

All plates were broad-rolled to 38-inch-long material of nominally 0.05-inch thickness, at progressively decreasing temperatures in the interval of 1350 C to 1150 C. Each sheet was stress relieved 10 minutes at 1050 C, then cut into equal pieces and matched to make up packs containing three to four sheets each.

Pack No.	Sheet Numbers	Number of Passes	Temp,(a) C	Comments
				C. Finish Rolling
1	3-1, 3-2, 5-1, 5-2	2	900	All packs cross-rolled, relative to last pass in intermediate rolling
		2	700	
		4	600	
		4	500	
		2	400	
		2	500	
		8	400	
2	4-1, 4-2, 6-1, 6-2	2	900	Same procedure as for Pack 1
		2	700	
		4	600	
		4	500	
		2	400	
		2	500	
		8	400	
3	1-2, 2-1, 2-2	2	900	
		4	700	
		4	600	
		2	500	
		4	450	
		2	400	
		2	350	
		2	400	
		2	350	
		2	400	
		2	350	
		2	400	
		2	350	
		4	400	
		1	400	
				All finished sheets were stress relieved 5 minutes at 1000 C, caustic cleaned and acid etched.

(a) Each pack reheated after each two passes.

TABLE 11. ROLLING OF 0.010-INCH-THICK SHEET

Pass No.	Mill Setting, inch	Temp, C	Comments
			A. Breakdown Rolling (All Material)
1	0.900	1475	Long rolled
2	0.700	1475	Cross rolled after Pass 2
3	0.500	1475	
4	0.300	1475	
5	0.215	1375	
6	0.215	1375	Cross rolled after Pass 6
7	0.150	1375	
8	0.140	1375	Stress relieved 5 minutes at 1150 C, caustic cleaned and acid etched, inspected, and conditioned

B. Intermediate Rolling (All Material)

All plates were broad-rolled from a nominal thickness of 0.230-inch to 0.050-inch at progressively decreasing temperatures in the interval of 1350 C to 1150 C. Each sheet was stress relieved 10 minutes at 1050 C, then cut into equal pieces and matched to make up packs containing three to four sheets each. These packs were then rolled, at progressively decreasing temperatures in the interval of 900 C to 350 C, reheating each pack after each two passes. The procedure used was similar to that described for 0.020-inch sheet in Table 10. Rolling on each pack was continued until each sheet reached a nominal thickness of 0.025-inch. All sheets were stress relieved 5 minutes at 1000 C, caustic cleaned, and acid etched.

Two packs, consisting of ten and nine sheets, respectively, were assembled and rolled to finished thickness as follows:

Pack 1, Sheets 1-10, inclusive		Pack 2, Sheets 11-19, inclusive	
No. of Passes	Mill Setting, inch	No. of Passes	Mill Setting, inch
	C. Finish Rolling		
2	0.225	3	0.200
3	0.185	3	0.165
3	0.150	3	0.150
2	0.125	3	0.150
2	0.125	3	0.125
2	0.105	3	0.125
2	0.105	2	0.100
3	0.090	2	0.085
3	0.080	2	0.070
2	0.070	2	0.060
3	0.070	2	0.060
3	0.060	2	0.050
3	0.055	2	0.050
2	0.050	2	0.040
1	0.045	2	0.040
3	0.050	2	0.035
		3	0.035
		2	0.035

Each pack was reheated to 950 C to 1000 C prior to the initial rolling pass. Reheating to the same temperature range was done prior to each change in mill setting.

All finished sheets were stress relieved 5 minutes at 1000 C, caustic cleaned, and acid etched.

TABLE 12. CHEMICAL ANALYSES OF SHEET

Sheet Thickness, inch	Sheet No.	Impurity Content, ppm					
		O_2	N_2	C	Mo	Fe	Si
0.010	1	40	60	10	20	20	—
0.020	5-1	20	30	10	30	50	—
0.060	1	20-10	60-40	<10-<10	30-30	80-50	30-<10
	5	20-20	50-50	<10-<10	70-70	50-50	10-10
	6	30	50-50	10-<10	50-30	50-100	10-10
	7	40-20	50-50	<10-<10	70-80	50-50	10-10
	10	30-10	40-20	10-<10	30-30	30-50	10-10
	19	10-30	50-50	<10-<10	50-40	10-10	10-<10
Average		24	47	8	48	48	11
95% prob. limits		0/51	25/69	6/10	5/91	0/103	0/14
0.100	66	20-20	30-50	<10-<10	50-30	30-50	10-10
	68	90-60	50-40	20-10	50-40	20-10	10-10
	71	50-30	30-60	10-10	30-100	20-50	10-10
	122	60-20	50-40	<10-<10	30-30	10-50	10-<10
	123	40-30	50-50	20-10	20-30	50-50	<10-<10
	128	30-40	50-40	10-10	50-30	50-50	<10-<10
Average		41	45	11	41	38	9
95% prob. limits		0/87	25/65	2/21	0/87	0/77	7/11
0.250	110	20	30	40	60	50	<10

TABLE 13. TENSILE PROPERTIES OF 0.250-INCH-THICK PLATE NO. 110

Test Temp, F	Test Direction	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, % in 1 inch
1800	Long.	60	55	9
	Trans.	58	53	10
	45°	-	-	-
2000	Long.	56	52	8
	Trans.	59	57	10
	45°	59	56	10

TABLE 14. TENSILE PROPERTIES OF 0.100-INCH-THICK SHEET

Sheet No.	Test Temp, F	Transverse Test Direction UTS, ksi	YS, ksi	Elongation % in 1 in.	RA, %	Longitudinal Test Direction UTS, ksi	YS, ksi	Elongation % in 1 in.	RA, %
66	1000	80	75	12	0	79	73	10	17
		72	71	4	1	79	71	13	51
		86	79	9	45	--	--	--	--
		80	74	4	1	--	--	--	--
68	1000	91	75	7	1	91	84	9	44
		88	79	3	1	92	85	10	57
		91	78	9	72	--	--	--	--
		85	72	9	73	--	--	--	--
	2000	73	62	9	74	--	--	--	--
		74	60	10	64	--	--	--	--
		65	55	9	65	--	--	--	--
		64	54	9	87	--	--	--	--
71	1000	83	70	10	88	85	72	7	8
		83	70	9	87	83	74	7	45
	2000	75	56	9	75	--	--	--	-
		76	57	10	73	--	--	--	--
122	1000	92	68	9	51	92	71	8	53
		89	66	9	54	90	71	9	49
		80	63	10	89	--	--	--	--
		80	63	10	79	--	--	--	--
	2000	72	59	12	57	--	--	--	--
		74	58	12	74	--	--	--	--
		72	63	12	79	--	--	--	--
		71	62	13	85	--	--	--	--
123	1000	86	71	10	78	91	76	10	55
		86	70	11	75	90	76	10	40
		90	77	10	53	--	--	--	--
		91	77	10	48	--	--	--	--
	2000	72	57	9	73	--	--	--	--
		71	58	9	73	--	--	--	--
		72	58	8	60	--	--	--	--
		75	58	8	76	--	--	--	--
128	1000	87	74	10	50	87	74	10	48
		87	74	10	52	87	74	10	55
		89	70	9	39	--	--	--	--
		88	70	10	42	--	--	--	--
	2000	69	52	10	81	--	--	--	--
		69	51	10	75	--	--	--	--
		75	62	14	73	--	--	--	--
		71	59	13	69	--	--	--	--

TABLE 15. TENSILE PROPERTIES OF 0.060-INCH-THICK SHEET

Sheet No.	Test Temp, F	Transverse Test Direction UTS, ksi	YS, ksi	Elongation % in 1 in.	RA, %	Longitudinal Test Direction UTS, ksi	YS, ksi	Elongation % in 1 in.	RA, %
1	1000	94	86	8	65	88	81	8	55
		95	87	6	47	88	78	8	52
		96	84	8	47	--	--	--	--
		95	89	10	50	--	--	--	--
	2000	72	60	9	46	--	--	--	--
		74	61	9	54	--	--	--	--
		76	56	8	67	--	--	--	--
		75	55	9	70	--	--	--	--
5	1000	101	88	7	35	91	91	8	51
		101	86	7	45	91	91	7	43
		97	89	8	34	--	--	--	--
		94	88	8	54	--	--	--	--
	2000	73	63	10	52	--	--	--	--
		77	66	10	60	--	--	--	--
		71	60	8	54	--	--	--	--
		85	73	8	50	--	--	--	--
6	1000	93	74	8	31	84	73	7	52
		91	81	5	49	82	70	6	57
		98	85	7	38	--	--	--	--
		98	85	7	52	--	--	--	--
	2000	72	66	9	47	--	--	--	--
		82	71	10	61	--	--	--	--
		76	62	10	64	--	--	--	--
7	1000	94	83	7	53	88	68	8	51
		93	83	7	43	88	68	8	52
		94	84	9	49	--	--	--	--
		94	84	9	27	--	--	--	--
	2000	77	68	8	67	--	--	--	--
		75	57	8	75	--	--	--	--
		73	53	10	69	--	--	--	--
10	1000	96	89	9	55	93	88	9	59
		93	75	9	56	96	88	7	62
		100	88	8	46	--	--	--	--
		100	88	9	48	--	--	--	--
	2000	82	59	7	58	--	--	--	--
		77	55	9	47	--	--	--	--
		80	63	11	49	--	--	--	--
		80	62	11	47	--	--	--	--
19	1000	90	85	9	49	88	82	8	43
		89	83	9	49	87	79	8	56
		98	92	9	52	--	--	--	--
		99	92	8	54	--	--	--	--
	2000	70	60	9	62	--	--	--	--
		74	62	9	49	--	--	--	--
		77	66	10	72	--	--	--	--
		81	68	10	55	--	--	--	--

TABLE 16. TENSILE PROPERTIES OF 0.010-INCH AND 0.020-INCH-THICK SHEET

Sheet No.	Test Temp, F	Transverse Test Direction UTS, ksi	YS, ksi	Elongation, % in 1 inch	Longitudinal Test Direction UTS, ksi	YS, ksi	Elongation, % in 1 inch
		0.010-Inch Sheet					
1	1000	144	--	4	130	101	4
		134	105	4	--	--	--
	2000	79	49	7	--	--	--
15	1000	137	117	4	129	97	--
	2000	73	64	7	--	--	--
		86	73	6	--	--	--
		0.020-Inch Sheet					
3-1	1000	126	114	4	--	--	--
	2000	83	69	9	--	--	--
		86	71	9	--	--	--
5-1	1000	122	109	5	--	--	--
		135	117	5	--	--	--
	2000	85	77	6	--	--	--
		83	66	8	--	--	--

TABLE 17. 1000 F NOTCHED TENSILE STRENGTH

Sheet Thickness, inch	Sheet No.	Test Direction	Notched Strength, ksi
0.060	1	Trans.	105
		Long.	107
	5	Trans.	97
		Long.	101
	6	Trans.	105
		Long.	101
	10	Trans.	113
		Long.	103
	19	Trans.	94
0.100	68	Trans.	40
		Long.	92
	71	Long.	86
	122	Trans.	92
		Long.	103
	123	Trans.	107
		Long.	78
	128	Trans.	75
		Long.	97

TABLE 18. PROBABILITY LIMITS OF TENSILE PROPERTY DATA

Sheet Thickness, inch	Test Temp, F	Test Direction	95% Probability Limit UTS, ksi	YS, ksi	Elongation % in 1 in.	90% Probability Limit UTS, ksi	YS, ksi	Elongation % in 1 in.
0.060	1000	Trans.	89/102	76/95	6/11	90/101	78/93	6/10
		Long.	76/105	61/99	6/10	79/103	64/95	6/9
	2000	Trans.	62/93	51/73	7/12	65/90	53/71	7/11
0.100	1000	Trans.	75/96	63/82	3/14	—	—	—
		Long.	77/98	65/85	6/13	—	—	—
	2000	Trans.	65/79	51/65	6/14	—	—	—

TABLE 19. BEND DUCTILITY OF 0.060-INCH-THICK SHEET

Sheet No.	Bend Transition Temperature,(a) F
1	725
	650
5	410
	555
6	775
	730
7	460
	660
10	400
	<350
19	460
	<360

(a) Values given represent 4T transition temperatures determined on samples cut from opposite ends of each sheet in the stress relieved-condition.

TABLE 20. HARDNESS VERSUS ANNEALING TEMPERATURE

Sheet Thickness, inch	Sheet No.	Hardness, VHN, 2000 g load					
		Stress Relieved	Annealed 1 Hour at: 1000 C	1100 C	1200 C	1300 C	1400 C
0.010	1	486(a)	—	475(a)	470(a)	417(a)	—
	15	501(a)	—	481(a)	471(a)	452(a)	—
0.020	5-1	517(a)	—	494(a)	482(a)	455(a)	—
0.060	1	473	469	468	463	450	357
	5	485	475	481	462	431	377
	6	471	471	464	465	455	370
	7	465	471	458	463	433	368
	10	478	468	472	470	460	378
	19	472	486	467	464	445	376
0.100	66	451	455	450	449	370	348
	68	467	467	460	448	394	359
	71	456	469	448	447	397	358
	122	463	457	458	457	418	362
	123	462	452	459	442	382	358
	128	445	454	457	451	414	366
0.250	99	440	—	—	—	—	—
	103	449	—	—	—	—	—
	110	443	440	440	436	440	369

(a) 500g.

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1	Thermal Properties of Titanium and Titanium Alloys, August 25, 1958 (PB 161152, $0.50)
2	Some Notes on Safe Handling Practices for Beryllium, September 22, 1958 (PB 161153, $0.50)
3	Recent Advances in Titanium Technology, October 24, 1958 (PB 161154, $0.50)
*4	Effects of High Strain Rates and Rapid Heating on the Tensile Properties of Titanium Alloys, December 29, 1958 (PB 161155, $0.50)
*5	The Influence of Sheet Thickness on Tensile Properties of Metal Sheet, January 23, 1959 (PB 161156, $0.50)
6	The Status of Chromium-Base Alloy Development, January 30, 1959 (PB 161157, $0.50)
7	Implications of Rhenium Research in the Design of Refractory Metals, February 2, 1959 (PB 161158, $0.50)
8	Elevated-Temperature Mechanical Properties and Oxidation Resistance of Columbium and Its Alloys, February 4, 1959 (PB 161159, $0.50)
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12	Some Metallurgical Considerations in Forging Molybdenum, Titanium, and Zirconium, March 25, 1959 (PB 161162, $0.50)
*13	Joining of Beryllium, March 30, 1959 (PB 161163, $0.50)
*14	Physical and Mechanical Properties of Molybdenum and the Mo-0.5Ti Alloy, April 10, 1959 (PB 161164, $0.50)
15	Mechanical- and Physical-Property Data on Modified 12 Per Cent Chromium Martensitic Stainless Sheet Steels for Airframe Applications, April 18, 1959 (PB 161165, $0.50)
16	Glass-Bonded Refractory Coatings for Iron- or Nickel-Base Alloys, April 25, 1959 (PB 161166, $0.50)
17	Future Application Trends for Titanium and Steel in Military Aircraft, May 8, 1959 (PB 161167, $0.50)
18	Fabrication of 17-7PH and PH15-7Mo Stainless Steel by Bend Rolling, Deep Drawing, and Spinning, May 15, 1959 (PB 161168, $0.50)
19	The Availability and Properties of Rhenium, May 22, 1959 (PB 161169, $0.50)
20	The Properties of Magnesium-Thorium Alloys, May 29, 1959 (PB 161170, $0.50)
21	Machining of Beryllium, June 5, 1959 (PB 161171, $0.50)
*22	Routing of Titanium Sheet, June 12, 1959 (PB 161172, $0.50)
23	Band Sawing of Titanium and Titanium Alloys, July 1, 1959 (PB 161173, $0.50)
24	Hacksawing of Titanium and Titanium Alloys, July 6, 1959 (PB 161174, $0.50)
25	Profile Milling Titanium and Its Alloys, July 10, 1959 (PB 161175, $0.50)
26	Spindle Shaping of Titanium Sheet, July 15, 1959 (PB 161176, $0.50)
*27	Arc Welding of High-Strength Steels for Aircraft and Missile Structures, July 31, 1959 (PB 161177, $0.50)
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13. ABSTRACT

A brief review and analysis is presented of the tungsten sheet rolling program performed by the Fansteel Metallurgical Corporation for the Department of the Navy. Emphasis is placed on detailing the procedures which were evolved for the production of 113 plates and sheets of various gages. Selected property data on these materials are also presented.

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